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Ecological problems and ecological restoration zoning of the Aral Sea

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Abstract: The Aral Sea was the fourth largest lake in the world but it has shrunk dramatically as a result of irrational human activities, triggering the "Aral Sea ecological crisis". The ecological problems of the Aral Sea have attracted widespread attention, and the alleviation of the Aral Sea ecological crisis has reached a consensus among the five Central Asian countries (Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan, and Turkmenistan). In the past decades, many ecological management measures have been implemented for the ecological restoration of the Aral Sea. However, due to the lack of regional planning and zoning, the results are not ideal. In this study, we mapped the ecological zoning of the Aral Sea from the perspective of ecological restoration based on soil type, soil salinity, surface water, groundwater table, Normalized Difference Vegetation Index (NDVI), land cover, and aerosol optical depth (AOD) data. Soil salinization and salt dust are the most prominent ecological problems in the Aral Sea. We divided the Aral Sea into 7 first-level ecological restoration subregions (North Aral Sea catchment area in the downstream of the Syr Darya River (Subregion I); artificial flood overflow area in the downstream of the Aral Sea (Subregion II); physical/chemical remediation area of the salt dust source area in the eastern part of the South Aral Sea (Subregion III); physical/chemical remediation area of severe salinization in the central part of the South Aral Sea (Subregion IV); existing water surface and potential restoration area of the South Aral Sea (Subregion V); Aral Sea vegetation natural recovery area (Subregion VI); and vegetation planting area with slight salinization in the South Aral Sea (Subregion VII)) and 14 second-level ecological restoration subregions according to the ecological zoning principles. Implementable measures are proposed for each ecological restoration subregion. For Subregion I and Subregion II with lower elevations, artificial flooding should be carried out to restore the surface of the Aral Sea. Subregion III and Subregion IV have severe salinization, making it difficult for vegetation to grow. In these subregions, it is recommended to cover and pave the areas with green biomatrix coverings and environmentally sustainable bonding materials. In Subregion V located in the central and western parts of the South Aral Sea, surface water recharge should be increased to ensure that this subregion can maintain normal water levels. In Subregion VI and Subregion VII where natural conditions are suitable for vegetation growth, measures such as afforestation and buffer zones should be implemented to protect vegetation. This study could provide a reference basis for future comprehensive ecological management and restoration of the Aral Sea.

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1 Introduction

The Aral Sea is located in the arid region of Central Asia. The name Aral Sea originates from the Turkish word "aral", which means island (Glantz, 2007). The Aral Sea region was part of the ancient Silk Road, connecting the east and west for trade and cultural communication. In addition, the Aral Sea region has a long history of irrigated agriculture, and the formation and development of ancient civilizations such as Ferghana and Bukhara were closely linked to the development of irrigation culture (Andrianov and Mantellini, 2016). The Aral Sea was once the fourth largest lake in the world (Micklin, 2010). However, since the 1960s, due to factors such as land reclamation and water diversion from the Karakum Canal to irrigate desert areas, the amount of water entering the Aral Sea has decreased and the water surface has shrunk dramatically, resulting in the globally recognized "Aral Sea ecological crisis" (Micklin, 1988; Indoitu et al., 2015).

Currently, the area of the Aral Sea has shrunk by approximately 90%, and the ecological crisis is still worsening (Micklin, 2007; Yang et al., 2020). The destruction of the ecosystem surrounding the Aral Sea has led to a decline in soil and water conservation capacity and significant vegetation degradation (Xu et al., 2016; Jiang et al., 2020). Moreover, the reduced water volume in the Aral Sea has resulted in an increase in salinity, causing the mass death or extinction of water organisms (Qadir et al., 2009). During the period 1961–1978, when the salinity of the Aral Sea rose sharply, the carp catches fell from 9940 to 100 t (Ermakhanov et al., 2012); and when the salinity exceeded 18 g/L, the Aral Sea completely lost its fishery (Ermakhanov et al., 2012). Worse still, as a result of salt accumulation and high winds, the dried-up part of the Aral Sea has become a source of salt and dust storms in the region, seriously endangering the health and livelihood of local residents (Indoitu et al., 2015; Chen et al., 2022; Wang et al., 2022). In Turkmenistan, 50% of all reported illnesses in children are respiratory in nature, which may be related to salt dust from the Aral Sea (UNDP, 1995). To effectively manage the ecological environment in the Aral Sea, it is necessary to carry out ecological restoration zoning in the Aral Sea and develop implementable and targeted zoning plans.

The deterioration of the ecological environment of the Aral Sea has received widespread attention from the international community, and alleviating the Aral Sea ecological crisis has become an important part of the current work in Central Asian countries (Kotlyakov, 1991; Horst et al., 2005; Micklin and Aladin, 2008; Wang et al., 2023a). In the past decades, many ecological management measures have been implemented to restore the ecological environment of the Aral Sea. In 2008, in collaboration with Uzbekistan's Forestry Research Institute, the German Agency for Technical Cooperation (GTC) planted black saxaul (*Haloxylon aphyllum*) in the central dry regions of the Aral Sea to reduce sand dust (Xenarios et al., 2019). Kazakhstan has built the Kok-Aral dam to ensure the restoration of the North Aral Sea and developed measures to reduce the discharge of industrial effluents into the Aral Sea (Micklin, 2016; Rzymski et al., 2019). However, previous governance measures did not consider the spatial variability of ecological problems in the Aral Sea and lacked regional planning and governance, so the ecological environment of the Aral Sea is undergoing continuous deterioration. To effectively manage the ecological environment of the Aral Sea, it is necessary to carry out ecological restoration zoning in the Aral Sea and develop implementable and targeted zoning plans. Ecological restoration zoning is part of ecological zoning, which was first proposed by Bailey (1976) in the United States, and since then the principles, indicators, and methods of ecological zoning have been widely discussed by researchers in various countries and regions around the world (Fischer et al., 2021; Xu et al., 2022). Ecological zoning research has developed rapidly and changed from ecological

issue-oriented, following the principles of natural zoning and the degree of development of ecological issues, to restoration zoning for specific ecological issues (Liu et al., 2017; Xu et al., 2022). Ecological restoration zoning emphasizes the identification of key ecological problems for zoning and proposes corresponding restoration measures based on the current status of ecosystem degradation and restoration. With the rapid development of remote sensing and geographical information system (GIS) technologies, GIS spatial analysis and mapping technology have been widely applied to carry out ecological restoration zoning for purposes such as salinization control and desertification restoration (Akbari et al., 2020), providing technical support for regional ecological restoration and promoting ecological management.

This study mapped the ecological governance regions of the Aral Sea, which can provide a reference basis for the ecological and environmental governance of the Aral Sea as well as other similar regions in the world. Based on the above considerations, this study used remote sensing and GIS technologies combined with data from satellite images, surface water, groundwater table, soil salinity, soil type, vegetation distribution, land cover, and aerosol optical depth (AOD) to map the ecological restoration subregions of the Aral Sea. Furthermore, implementable restoration measures are proposed for each ecological restoration subregion. The results of the study are expected to provide scientific guidance for future ecological governance and restoration of the Aral Sea.

2 Study area

The Aral Sea is located between Kazakhstan and Uzbekistan (43°13′–46°56′N, 57°56′–62°18′E) and mainly drained by the Amu Darya River and Syr Darya River (Fig. 1). It is the coccyx lake of both rivers and the second-largest inland saltwater lake in Asia after the Caspian Sea (Micklin, 2010). The Aral Sea has a typical continental climate. Specifically, the annual precipitation is less than 100 mm, the monthly average temperature in February is –12°C in the north and –6°C in the south, and the monthly average temperature in July is 23°C in the north and 26°C in the south

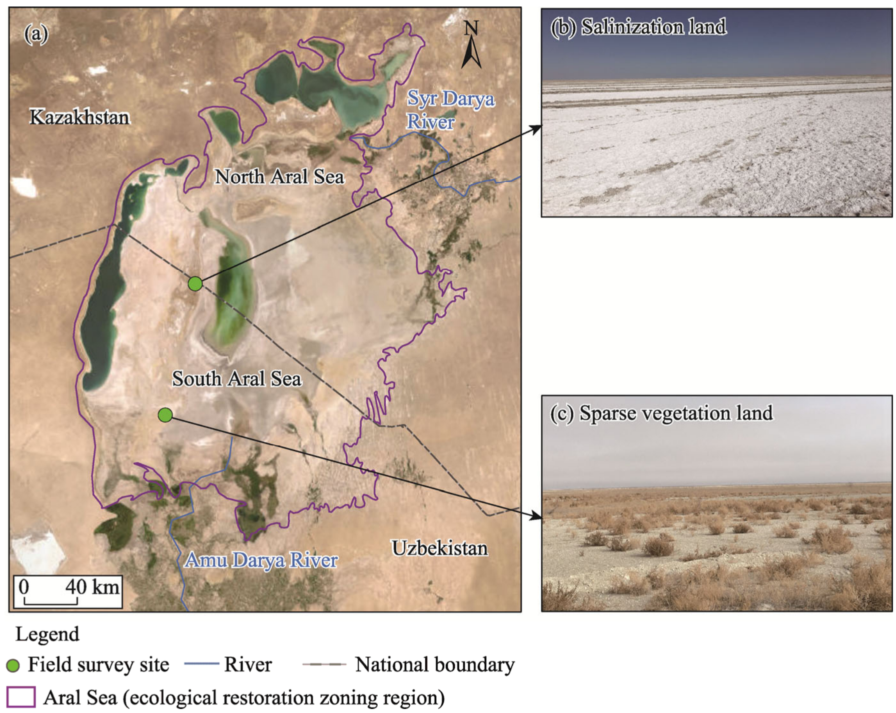


Fig. 1 Geographical location of the Aral Sea and the extent of ecological restoration zoning region based on the satellite image (a), and the landscape of the field survey sites (b and c). The left panel was from the Esri, Maxar, Geographics and the GIS User Community (https://community.esri.com/).

(Boomer et al., 2000; Shibuo et al., 2007). Until the 1960s, evaporation from the Aral Sea was approximately equal to the inflow (Cretaux et al., 2013; Wang et al., 2023b). Currently, however, most of the Aral Sea has disappeared, gradually shrinking into two parts: the South Aral Sea located in Uzbekistan and the North Aral Sea located mainly in Kazakhstan. In 1993, the five Central Asian countries (Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan, and Turkmenistan) established the Interstate Commission for Water Coordination (ICWC) and the International Fund for Saving the Aral Sea (IFAS) to manage the ecological crisis of the Aral Sea.

3 Materials and methods

3.1 Data sources

The ecological problems of the Aral Sea are most prominent in arid areas where soil salinization and salt and dust storms occur (Abuduwaili et al., 2010; Shen et al., 2016). Salt and dust storms are not only related to soil salinization but also linked to soil types, with dry sandy soils being more prone to dusting (Stulina and Sektimenko, 2004). Groundwater table is critical to the growth of vegetation, and the decline of groundwater table can lead to the degradation or even death of vegetation. In addition, groundwater table is a prerequisite for vegetation recovery. Therefore, the data used in this study mainly included the degree of soil salinity, soil type, groundwater table, land cover, and field survey data. Soil salinity, soil type, and groundwater table were obtained by vectorizing thematic maps provided by the United Nations Environment Programme (UNEP) in 2008 (Dukhovny et al., 2008). Land cover with 30-m spatial resolution for the years 1990 and 2018 as well as its field survey data (salinization, vegetation type, etc.) for the period 2018–2019 were obtained from the Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, China. Twenty field samples were collected from two field survey sites to investigate the state of the ecological environment of the Aral Sea. We divided the land use types into six categories: shrubland, grassland, wetland, bare land, salt marsh, and water body based on previous studies (Shen et al., 2016; Yu et al., 2021). AOD data in 2000 and 2018 from Moderate Resolution Imaging Spectroradiometer (MODIS) with 1-km spatial resolution were used to reveal the spatial distribution characteristics of salt dust in the Aral Sea. Landsat TM and OLI imagery was used to calculate the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI). Areas with NDVI<0.2 were defined as no vegetation cover and NDVI≥0.2 as vegetation cover (Sobrino et al., 2001; Momeni and Saradjian, 2007); NDWI was used to determine the existing water of the Aral Sea. The digital elevation model (DEM) was generated using data from the ZiYuan-3 surveying satellite (ZY-3). The details of the data used in this study are listed in Table 1.

Table 1 Description of the data used in this study

Data	Acquisition time	Spatial resolution (m)	Source
MODIS AOD	2000 and 2018	1000	https://lpdaac.usgs.gov/
Landsat5 TM	1990 and 2000	30	https://earthexplorer.usgs.gov/
Landsat8 OLI	2018	30	https://earthexplorer.usgs.gov/
Soil type	2008	30	UNEP (Dukhovny et al., 2008)
Groundwater table	2008	30	UNEP (Dukhovny et al., 2008)
Soil salinity	2008	30	UNEP (Dukhovny et al., 2008)
Land cover	1990 and 2018	30	http://www.egi.ac.cn/
DEM	-	5	ZiYuan-3 surveying satellite (http://114.116.226.59/chinese/satellite/chinese/zy3)
Water area	1974–2020	-	http://www.cawater-info.net

Note: MODIS, Moderate Resolution Imaging Spectroradiometer; AOD, aerosol optical depth; UNEP, United Nations Environment Programme; DEM, digital elevation model. - means no acquisition time or spatial resolution.

3.2 Principles of zoning

Ecological restoration zoning should follow the zoning principles to improve the rationality and effectiveness of zoning. The widely used zoning principles include geographical unit integrity, dominant factors, and consistency of control strategies (Allen et al., 2002; Wang et al., 2020). The geographical unit integrity principle emphasizes that there is a high degree of similarity in the occurrence and development of ecological problems in the same geographical unit. Therefore, maintaining the relative integrity of geographical units in zoning can help to effectively identify ecological problems in different regions. The dominant factor principle implies that the dominant factors of ecological problems in each region should be clarified when ecological zoning is carried out, which will contribute to the formulation of more targeted restoration measures. The principle of the consistency of control strategies requires that within the same zoning unit, ecological governance measures should be relatively consistent, which is the basic guarantee of the rationality and practicality of zoning.

3.3 Methods of zoning

This study divided the Aral Sea into two levels of ecological restoration subregions. First, indicators reflecting the ecological status of the Aral Sea were selected on the basis of the results of previous studies (Di et al., 2008, 2009), including salinization, vegetation cover (reflected by NDVI), sand and dust storms, existing water surface (reflected by NDWI), land cover, and soil type. Then, with reference to previous zoning methods (Zhao et al., 2013) and on the basis of GIS spatial analysis, we visualized and overlaid the layers of the abovementioned indicators to identify the dominant factors of ecological problems in different subregions of the Aral Sea by visual interpretation. Finally, following the principles of zoning and the dominant factors of the regions, the boundaries of the regions were determined and adjusted to form the first-level subregions. Given that the Aral Sea is a transboundary lake belonging to Uzbekistan and Kazakhstan, and to reduce the conflicts of interest between the two countries in the restoration of the Aral Sea, we further divided the first-level zoning into the second-level zoning according to the national boundary between Uzbekistan and Kazakhstan.

4 Results and discussion

4.1 Main ecological problems in the Aral Sea

The Aral Sea is supplied primarily by the Amu Darya River and Syr Darya River. Irrational water usage accounts for 86% of the Aral Sea's retreat, while the effects of climate change account for only 14% (Bekzod et al., 2021). During the Soviet period, a large number of reservoirs, hydroelectric power stations, and aqueducts were built on the Amu Darya River and Syr Darya River. The Karakum Canal, known as the "lifeblood of Turkmenistan", is the largest water diversion project on the Amu Darya River, affecting 60% of the population of Turkmenistan. The Karakum Canal receives 190.00×10^{8} m^3 of water from the Amu Darya River each year, which accounts for approximately 33% of the Amu Darya River's total water volume (Spoor, 1998). In addition, the Karshi Irrigation Canal diverts 33.00×10^{8}–52.50×10^{8} m^3 of water from the Amu Darya River every year. Figure 2 shows that the area of the Aral Sea declined from 57.00×10^{3} to 9.29×10^{3} km^2 during the period 1974–2020, with an average change rate of -1.04×10^{3} km^2/a. The areas of dramatic change in the Aral Sea are concentrated in the South Aral Sea (Fig. 2a), mainly because the water area in the center has been in a state of dynamic change. The currently stabilized water areas are the North Aral Sea in northern Kazakhstan and a small part of the South Aral Sea in western Uzbekistan. During the period 1974–2020, excessive diversion of water has left the Syr Darya River and Amu Darya River with no excess water to supply the downstream deltas. The deltaic network of the Amu Darya River and Syr Darya River has gradually disappeared and 95% of the marshes and wetlands have been degraded to saline deserts (Rudenko and Lamers, 2010; Jiang et al., 2019).

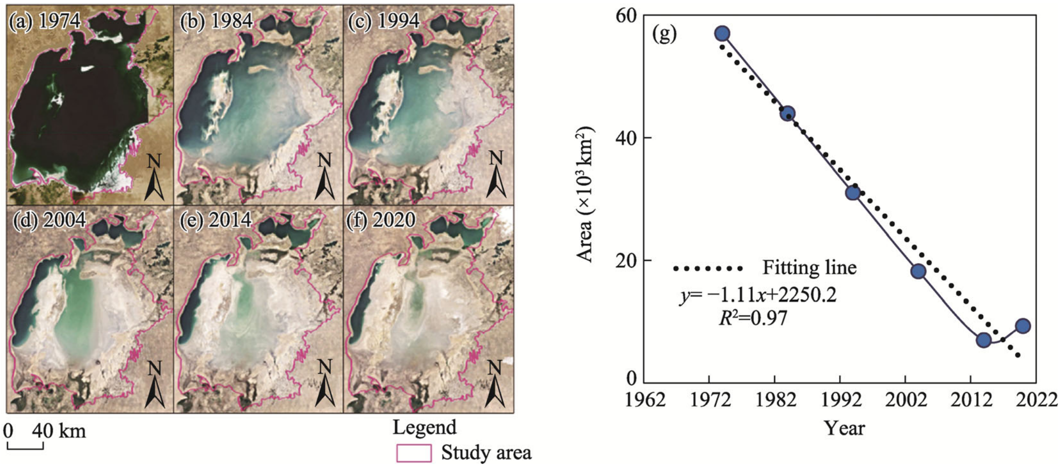


Fig. 2 Spatial (a–f) and temporal (g) variations in the water area of the Aral Sea from 1974 to 2020. The data were obtained from the Interstate Commission for Water Coordination of Central Asia (ICW) (http://www.cawater-info.net).

Over the last 60 a, the region of the Aral Sea that was drying out has experienced different vegetation succession processes, with the dominant vegetation gradually evolving from initially hydrophytic vegetation to xerophytic vegetation (Liliya, 2015; Shomurodov et al., 2021). The land cover changes from 1990 to 2018 (Fig. 3a and b) show that even though the area of grassland has increased from 1990 to 2018, most of the dry areas of the Aral Sea have been degraded to salt marsh (26.81×10^3 km^2) and bare land (23.40×10^3 km^2). The spatial pattern of NDVI indicates that in the Amu Darya River delta in the southern part of the Aral Sea, vegetation coverage is high (Fig. 3c and d) and the main vegetation type is grassland (Fig. 3a and b). Compared to the situation in 1990, the lower dry region of the North Aral Sea has evolved into an area suitable for vegetation growth in 2018, with a small amount of vegetation distributed.

The distribution and succession of vegetation are closely related to changes in hydrological regime and soil salinity (Liliya, 2015). We generated a map of the degree of soil salinity in the Aral Sea (Fig. 4a) based on the Food and Agriculture Organization of the United Nations (FAO) salinity classification criteria (FAO, 2005) and UNEP survey data in 2008 (Dukhovny et al., 2008). Severe salinization and salt soil are found mainly in the central part of the Aral Sea, where the terrain is lower (Fig. 4b) and the soil types are mainly salt soil and salt marsh (Fig. 4c). Areas of slight salinization are concentrated in the southern part of the North Aral Sea, where the terrain is higher (Fig. 4b) and the soil type is mainly meadow soil (Fig. 4c). Areas with no salinization are concentrated in the southern and northern parts of the Aral Sea, i.e., in the downstream of the deltas of the Amu Darya River and Syr Darya River. Soil salinization is closely related to groundwater table and, in general, the shallower the groundwater table is, the greater the degree of soil salinization is. Figure 4d shows that groundwater table is shallower (0.0–1.0 m) in the central part of the Aral Sea, while it is deeper in the eastern part (>5.0 m).

The drying of the Aral Sea has led to an increase in the salt concentration of the water, which rose from 9 g/L in 1957 to more than 70 g/L in 2003 (Micklin, 2010). The dried-up surface of the Aral Sea became a saline wasteland and a new source of sand and dust. Under the influence of wind, salt-sand (dust) storms formed and large quantities of salt were dispersed into the surrounding areas, causing the gradual desertification of the areas around the Aral Sea. Desertification of the Aral Sea has further led to the loss of land functions and the transport and deposition of toxic salt dust by the wind from the dry areas to the deltas, exacerbating the salinization of agricultural land in Central Asia (Indoitu et al., 2015; Issanova et al., 2015; Liu et al., 2020). In addition, dust storms containing salt and toxic elements can disrupt livestock and agricultural production, increasing the risk of respiratory diseases in the Amu Darya River delta

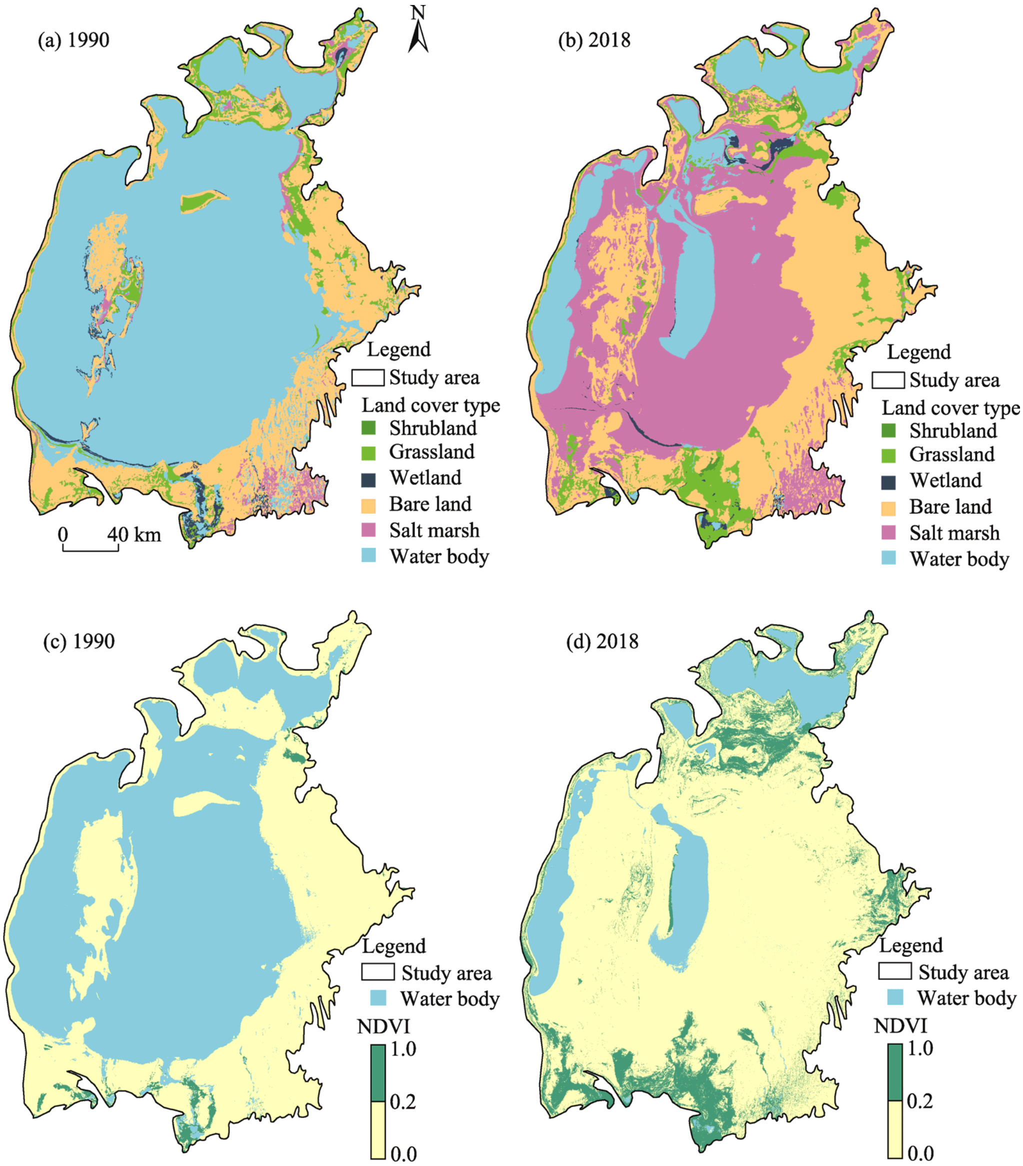


Fig. 3 Spatial distributions of land cover types (a and b) and NDVI (c and d) in the Aral Sea in 1990 and 2018. NDVI, Normalized Difference Vegetation Index.

(Crighton et al., 2011; Jiang et al., 2020). A higher AOD indicates a higher frequency of sand and dust storms. Figure 5 shows the spatial distributions of AOD in the Aral Sea in 2000 and 2018, and the results indicate a significant increasing trend of AOD from 2000 to 2018. In 2018, areas with higher AOD values are mainly distributed in the central part of the Aral Sea, where saline and desert soils are distributed (Figs. 4c and 5b).

The lowering of the water level, the shrinkage of the water surface, and the change of the substrate of the Aral Sea all affected the exchange of water and heat and weakened the climate-regulating function of the Aral Sea. Climatic conditions around the Aral Sea have changed, with summers becoming shorter, drier, and hotter and winters becoming increasingly longer and colder (He et al., 2022). Moreover, the decline of groundwater table in the Aral Sea has further exacerbated the drought. Extensive agricultural irrigation has led to the salinization of the land. Pesticides and fertilizers polluted agricultural drainage systems, leading to a decline in surface water and groundwater quality. The polluted water enters the drinking water system of the

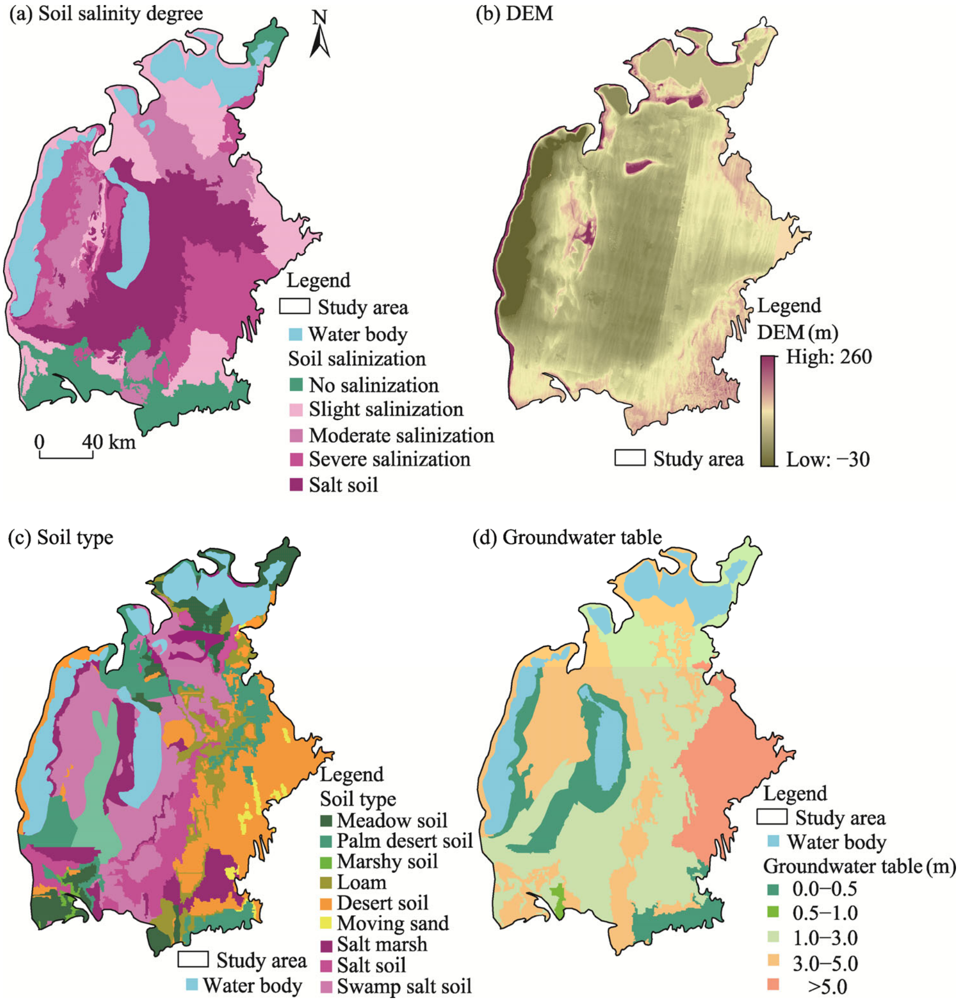


Fig. 4 Spatial distributions of soil salinity degree (a), DEM (b), soil type (c), and groundwater table (d) in the Aral Sea in 2008. DEM, digital elevation model.

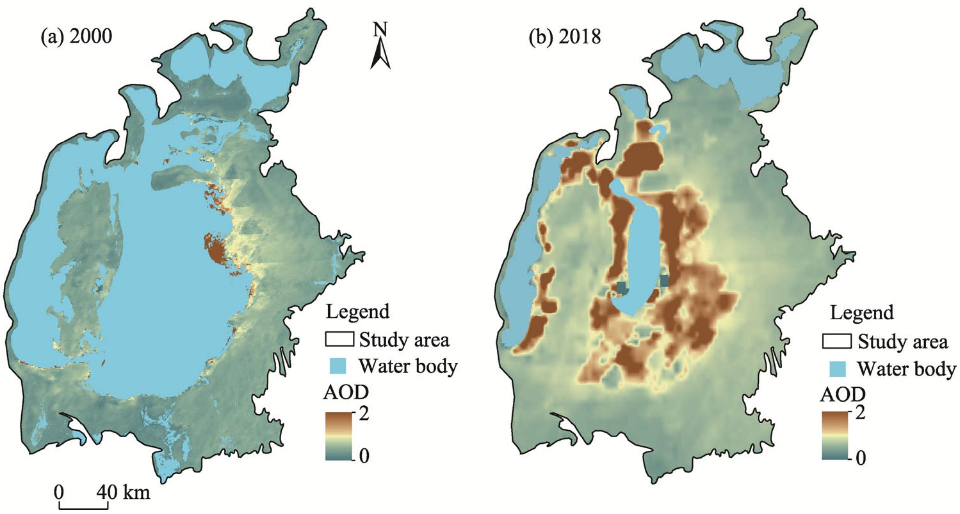
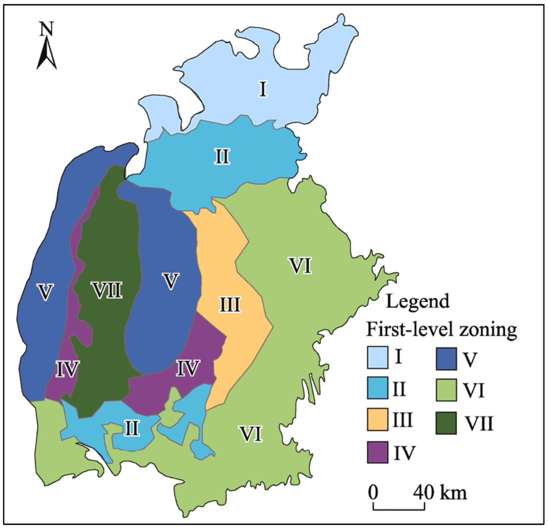


Fig. 5 Spatial distributions of AOD in the Aral Sea in 2000 (a) and 2018 (b). AOD, aerosol optical depth.

local residents through different routes, endangering human health (Kulmatov et al., 2021). Species diversity has also been affected by the ecological deterioration of the Aral Sea, characterized by the disappearance of six animal species or subspecies, the rarity of more than 20 species, and the disappearance of 30 bird species in the Amu Darya River delta from 1960 to 2000 (Zadereev et al., 2020).

4.2 First-level zoning of ecological restoration of the Aral Sea

The first-level zoning of ecological restoration of the Aral Sea divided the study area into seven subregions (Fig. 6). The largest subregions are the Aral Sea vegetation natural recovery area (Subregion VI) and existing water surface and potential recovery area in the South Aral Sea (Subregion V), with areas of 22.06×10^3 and 12.16×10^3 km^2, respectively. These are followed by the artificial flood overflow area in the downstream of the Aral Sea (Subregion II), North Aral Sea catchment area in the downstream of the Syr Darya River (Subregion I), and vegetation planting area with slight salinization in the South Aral Sea (Subregion VII), with areas of 9.26×10^3, 7.54×10^3, and 7.18×10^3 km^2, respectively. The subregions with the smallest areas are the physical/chemical remediation area of the salt dust source area in the eastern part of the South Aral Sea (Subregion III) and physical/chemical remediation area of severe salinization in the central part of the South Aral Sea (Subregion IV), with areas of 5.19×10^3 and 4.32×10^3 km^2, respectively.



First-level zoning	Name	Area (×10^3 km^2)
I	North Aral Sea catchment area in the downstream of the Syr Darya River	7.54
II	Artificial flood overflow area in the downstream of the Aral Sea	9.26
III	Physical/chemical remediation area of the salt dust source area in the eastern part of the South Aral Sea	5.19
IV	Physical/chemical remediation area of severe salinization in the central part of the South Aral Sea	4.32
V	Existing water surface and potential restoration area in the South Aral Sea	12.16
VI	Aral Sea vegetation natural recovery area	22.06
VII	Vegetation planting area with slight salinization in the South Aral Sea	7.18

Fig. 6 Spatial distribution of the first-level zoning of ecological restoration of the Aral Sea and the area of each subregion

4.3 Second-level zoning of ecological restoration of the Aral Sea

Based on the first-level zoning, we further divided the Aral Sea into 14 second-level subdivisions. According to the national boundary of the two countries, we divided Subregion II into Subregion II-1 in Kazakhstan and Subregion II-2 in Uzbekistan, with areas of 6.23×10^3 and 3.02×10^3 km^2, respectively (Table 2). Subregion III-1 is located in Kazakhstan with an area of 4.21×10^3 km^2 and Subregion III-2 is located in Uzbekistan with a smaller area (0.98×10^3 km^2). Subregion IV was divided into Subregion IV-1 in Kazakhstan and Subregion IV-2 in Uzbekistan. Subregion IV-2 has a larger area of 4.16×10^3 km^2, which indicates that salinization is more severe in Uzbekistan than in Kazakhstan in the Aral Sea region. Subregion V was divided into the Uzbekistan part (Subregion V-1) and Kazakhstan part (Subregion V-2). Subregion VI was divided into three subdivisions. Specifically, Subregion VI-1 in Kazakhstan and Subregion VI-2 in Uzbekistan are sandy areas with high topography, which have been dry for a long time, but according to the field surveys and NDVI monitoring, some desert vegetation is still preserved in these areas. Subregion

VI-3 in Uzbekistan is located in the downstream of the Amu Darya River where water resources are abundant and vegetation grows well. Subregion VII was divided into two subdivisions, mainly in Uzbekistan (Subregion VII-2), while the area in Kazakhstan is smaller (Subregion VII-1).

Table 2 Second-level zoning of ecological restoration of the Aral Sea

Second-level zoning	Name	Area ($\times10^3$ km^2)
I	North Aral Sea catchment area in the downstream of the Syr Darya River (Kazakhstan)	7.54
II-1	Artificial flood overflow area in the downstream of the Aral Sea (Kazakhstan)	6.23
II-2	Artificial flood overflow area in the downstream of the Aral Sea (Uzbekistan)	3.02
III-1	Physical/chemical remediation area of the salt dust source area in the eastern part of the South Aral Sea (Kazakhstan)	4.21
III-2	Physical/chemical remediation area of the salt dust source area in the eastern part of the South Aral Sea (Uzbekistan)	0.98
IV-1	Physical/chemical remediation area of severe salinization in the central part of the South Aral Sea (Kazakhstan)	0.16
IV-2	Physical/chemical remediation area of severe salinization in the central part of the South Aral Sea (Uzbekistan)	4.16
V-1	Existing water surface and potential restoration area in the South Aral Sea (Kazakhstan)	5.15
V-2	Existing water surface and potential restoration area in the South Aral Sea (Uzbekistan)	7.00
VI-1	Natural restoration area for vegetation of sandy land in the eastern part of the South Aral Sea (Kazakhstan)	11.47
VI-2	Natural restoration area for vegetation of sandy land in the eastern part of the South Aral Sea (Uzbekistan)	5.69
VI-3	Natural restoration area of vegetation in the downstream of the Amu Darya River in the South Aral Sea (Uzbekistan)	4.93
VII-1	Vegetation planting area with slight salinization in the South Aral Sea (Kazakhstan)	1.93
VII-2	Vegetation planting area with slight salinization in the South Aral Sea (Uzbekistan)	5.25

4.4 Ecological restoration measures of the Aral Sea

With reference to the experience of desertification control in the Tarim River Basin, China (Yu et al., 2022) as well as the local hydrological conditions, the degree of salinization, and the distribution of vegetation in each of the second-level subregions, we proposed the following zonal restoration measures (Fig. 7).

Subregion I (North Aral Sea catchment area in the downstream of the Syr Darya River) is recharged by the Syr Darya River in the north. This area has a slight degree of salinization and a higher vegetation coverage. In recent years, the surfaces of the North Aral Sea have been restored due to the construction of water storage dams in Kazakhstan (Wang et al., 2023b). It is recommended that artificial floods could be used to provide water recharge for the restoration of the surface in Subregion II-1 while maintaining the current water levels of the North Aral Sea.

Subregion II (artificial flood overflow area in the downstream of the Aral Sea) is mainly located in the southern part of the North Aral Sea and the southern part of the South Aral Sea, with low topography and high vegetation coverage. The large number of depressions intercepting surface runoff from the lower Amu Darya River and the Syr Darya River has led to a serious reduction in water flow to the Aral Sea. This subregion can be restored by artificial flooding to provide a certain amount of water to the Aral Sea. Subregion II-1 is located in Kazakhstan, and there are still small amounts of water body and wetlands in the downstream of the Syr Darya River; this subregion can be restored by diverting water from the Syr Darya River or by using flood irrigation techniques. Subregion II-2 is located in Uzbekistan, where the lower Amu Darya River has extensive wetlands and numerous tributary water systems. To protect the wetlands and deltaic water network in the lower Amu Darya River, artificial flood relief could be implemented. It should also be noted that artificial flooding should be implemented during the periods of abundant water to reduce conflicts with irrigated agriculture.

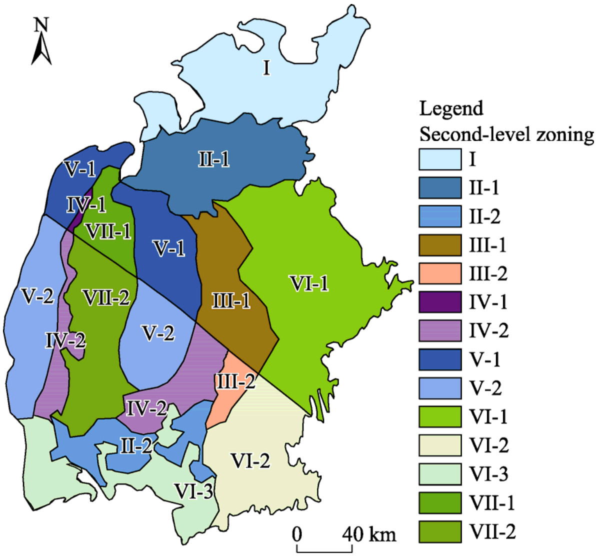


Fig. 7 Spatial distribution of the second-level zoning of ecological restoration of the Aral Sea. The names of the second-level subregions are shown in Table 2.

Subregion III (physical/chemical remediation area of the salt dust source area in the eastern part of the South Aral Sea) is located mainly in the eastern part of the South Aral Sea. This subregion has severe soil salinization, characterized by both typical dried saline-alkali soil and dry sandy soil. Dried saline-alkali soil can easily cause the formation of extremely harmful salt dust. The high salinity of the soil in this subregion makes it difficult for vegetation to grow, so this subregion is classified as a physical/chemical technical restoration area (Kim et al., 2020). In this subregion, it is recommended to cover and pave the ground surface with green bio-matrix coverings and environmentally sustainable bonding materials, as bonding materials such as urease adsorbent extracted from soybeans can not only absorb salt dust but also be degraded by the soil (Wu et al., 2020).

Subregion IV (physical/chemical remediation area of severe salinization in the central part of the South Aral Sea) is located mainly in the lakeshore area of the Aral Sea, where groundwater is shallow and soil salinity is high. The soil type is predominantly saline-alkali soil, making it difficult for vegetation to grow, and this subregion can be divided into physical/chemical technology remediation area. The second level of subdivisions (Subregion IV-1 in Kazakhstan and Subregion IV-2 in Uzbekistan) may be physically covered with a high density of gravels to prevent the formation of salt dust as the saline soil dries out.

Subregion V (existing water surface and potential restoration area of the South Aral Sea) is located mainly in the central and western parts of the South Aral Sea. The western part of the South Aral Sea still contains large areas of water surface with relatively stable water depths. The central part of the South Aral Sea also contains some water surface, but the dynamics of groundwater and water surface considerably change over time (Yang et al., 2020; Huang et al., 2022), and soil salinity in the surrounding exposed areas is extremely high, making it difficult for vegetation to survive; thus, this subregion is classified as a potential water surface restoration area. Buffer area could be established in Subregion V-1 (Kazakhstan) and Subregion V-2 (Uzbekistan) to minimize the disturbance from human activities (such as tourism) to the restoration of water surface. Surface water recharge should also be increased during drought years to ensure that this subregion can maintain normal water levels.

Subregion VI (Aral Sea vegetation natural recovery area) is located mainly in the eastern and southeastern parts of the Aral Sea Basin. This subregion, with its high topography, was the first area of the Aral Sea to dry up and has a low degree of salinization (Bekzod et al., 2021; Wang et

al., 2021). Vegetation coverage is higher in Subregion VI-1 (Kazakhstan), Subregion VI-2 (Uzbekistan), and Subregion VI-3 (Uzbekistan). Therefore, Subregion VI can be divided into areas for the natural restoration of vegetation, allowing the vegetation to grow naturally. In Subregion VI-1 (Kazakhstan) and Subregion VI-2 (Uzbekistan), forest belts with barrier effects can be established for natural conservation. Moreover, to solve the problem of water shortage in the desert, groundwater can be extracted instead of surface water to irrigate vegetation, which will reduce secondary salinization and further guarantee the growth of vegetation. Subregion VI-3 (Uzbekistan) is abundant in water resources, and groundwater can be extracted in localized areas to irrigate vegetation to sustain its growth.

Subregion VII (vegetation planting area with slight salinization in the South Aral Sea) is located mainly in the central part of the South Aral Sea, with high topography, low degree of salinization, and shallow groundwater table. The soil type is mainly residual meadow soil and swampy salt soil. Although there is some vegetation growing at present, the vegetation coverage is lower. In Subregion VII-1 (Kazakhstan) and Subregion VII-2 (Uzbekistan), some salt-tolerant desert species can be planted.

4.5 Implications and initiatives

With the rapid development of agriculture in the Aral Sea Basin in the 1960s, the depth, area, and volume of water in the Aral Sea showed a pronounced downward trend (Boomer et al., 2000). This has led to ecological deterioration in and around the Aral Sea, such as the ecological degradation of the Amu Darya River delta (Yu et al., 2019) and increased degree of soil salinization and desertification (Jiang et al., 2019; Yu et al., 2021). The ecological problems of the Aral Sea have been described as "the most worrying ecological disaster" in Central Asia and serve as a warning for sustainable development in arid areas. Northwest China and the Aral Sea Basin are both arid and semi-arid areas with similar climatic conditions, and their ecosystems are extremely sensitive to climate change and human activities. During the process of developing water resources in the inland river basins of arid and semi-arid regions, China should pay attention to the ecological problems and management experience of the Aral Sea Basin, and adhere to the scientific concept of sustainable development. Full consideration should be given to the ecological water of inland river basins, and the structure of regional productive and ecological water should be rationally allocated and adjusted to adhere to the path of sustainable development.

This study delineated the ecological and environmental restoration areas of the Aral Sea on a regional scale and provided a reference basis for the sustainable management of the Aral Sea. In future work, more detailed data should be obtained to construct reasonable and comprehensive indicators to guide the implementation of ecological restoration zoning. The evolution of the ecological environment in the Aral Sea has a bearing on the health and stability of the Aral Sea Basin and the entire Central Asian ecosystem; however, comprehensive restoration of the ecological environment in the Aral Sea is a long way off and requires the joint efforts of all Central Asian countries and the international community. As direct managers of the Aral Sea, Kazakhstan and Uzbekistan have taken several measures to restore the ecological environment of the Aral Sea. In the future, cooperation between the two countries should refer to the framework of the overall ecological balance of the Aral Sea to reduce conflicts and discrepancies in management approaches. As the major promoter of the Shanghai Cooperation Organization, China needs to uphold the concept of "a community with a shared future for humankind", actively implement the initiative—"One Belt, One Road", and promote the construction of the Green Silk Road. China should extend the technologies and successful experiences in the fields of water resources restoration, desertification control, ecological restoration, and remote sensing monitoring, demonstrating the nation's contribution to the ecological and environmental protection along the Silk Road Economic Belt. It is imperative that Chinese technologies and solutions for the ecological and environmental protection in Central Asian countries should be provided to help the Central Asian region achieve the United Nations (UN) Sustainable Development Goals (SDGs) by 2030.

5 Conclusions

The ecological problems of the Aral Sea Basin threaten the stability of ecosystems and the sustainable development of societies in this region and the Central Asian countries. This study revealed the main ecological problems of the Aral Sea and mapped the ecological zoning of the Aral Sea from the perspective of ecological restoration based on soil type, soil salinity, surface water, groundwater table, NDVI, land cover, and AOD data. We found that soil salinization and salt dust are the most prominent ecological problems in the Aral Sea. The areas with severe salinization and high frequency of salt and dust storms are mainly distributed in the central part of the Aral Sea. In the downstream of the North Aral Sea and the Amu Darya River delta, the degree of salinization is low and the vegetation coverage is high.

To manage the ecological problems of the Aral Sea, we divided the region into 7 first-level subregions and 14 second-level subregions. The largest of the seven first-level subregions are the Subregion VI and Subregion V, with areas of 22.06×10^3 and 12.16×10^3 km^2, respectively. Based on the second-level ecological restoration zoning, we proposed appropriate restoration measures. The restoration of the water level of the Aral Sea is particularly important for the maintenance of its ecological balance, and artificial irrigation should therefore be used in Subregion I and Subregion II to restore the area of the Aral Sea. It is important that artificial irrigation should be carried out in such a way as to minimize conflicts between ecological water and agricultural irrigation and avoid further depletion of the water resources of the Aral Sea. In Subregion III and Subregion IV, it is recommended to cover and pave the areas with green bio-matrix coverings and environmentally sustainable bonding materials. Surface water recharge in Subregion V should be increased to ensure that this subregion can maintain normal water levels. For Subregion VI and Subregion VII, measures such as afforestation and buffer zones should be implemented to protect vegetation.

Our study proposed a framework for the future ecological governance of the Aral Sea. However, there are still some limitations in this study. Firstly, due to the lack of data such as species richness, indicators reflecting biodiversity information were not included in the ecological restoration zoning. Secondly, this study did not consider the impact of human activities, such as agricultural irrigation, on ecological restoration zoning. The above limitations will be incorporated into future work to better support the sustainable management of the Aral Sea.

Conflict of interest

CHEN Xi is an Editor-in-Chief of Journal of Arid Land and was not involved in the editorial review or the decision to publish this article. LEI Jiaqiang is an editorial board member of Journal of Arid Land and was not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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